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Seasonal and Spatial Variations of Total Mass Flux around Coral Reefs in the Southern Ryukyus, Japan

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Total mass flux, size distribution of sediment particles and some chemical components such as total carbon (TC), total nitrogen (TN) and calcium carbonate ($CaCO_3$) were monitored monthly using a multi-cup sediment traps at seven coral reef sites (6 reef flat and 1 reef slope) of the Marine Protected Areas around Ishigaki, Kohama, Kuroshima and Iriomote Islands in the southern Ryukyus, Japan from September 2000 to September 2001. The size distribution of trapped sediments revealed mostly uni-modal fine sand to mud in the reef flat and gravelly to coarse sand in the reef slope. The total mass flux ranged between 0.54 to 872 $gm^{-2}d^{-1}$, and showed a pronounced seasonality (high in summer-autumn and low in spring) at each site, which was consistent with the rainfall and typhoon regime. Exceptionally high values were observed on the reef slope (Iriomote) in February–March 2001 (1533 $gm^{-2}d^{-1}$) owing to a large amount of bottom sediment re-suspension. On the reef flat (Todoroki South and North; Ishigaki), values obtained in July–August 2001 (872 $gm^{-2}d^{-1}$) and August–September 2001 (800 $gm^{-2}d^{-1}$) indicate the high terrestrial discharge from Todoroki River. Trapped sediment particles consist of $CaCO_3$ (1.2–27.1%) and a non-carbonate fraction (98.8–72.9%), which contains total carbon (4.9–26%), carbonate carbon (CO_2-C) (0.2–3.1%) and non-carbonate carbon (NC-C) (7.9–25.6%). Total nitrogen content was in the range 0.02–0.48%. TN is contained mainly in the carbonate fraction and NC-C may be contained in the non-carbonate fraction. The low TN/OC ratio of the trapped sediments suggests that they were mostly of terrestrial origin and that both fractions migrated. The high total mass flux derived from Todoroki River exceeded the threshold at which a lethal effect on coral community is caused. The results stress the importance of conducting seasonal studies of sedimentation over more than one year and at more than one location in south Japan coral reef ecosystems to gain an understanding of the processes controlling the total mass fluxes and their nutrients content, also to develop an awareness of how to prevent the damage of coral reef ecosystems and, if it does occur, to allow mitigation measures to be undertaken.

Keywords:
· Total mass flux,
· monitoring,
· sediment traps,
· coral reef,
· the southern Ryukyus, Japan.

1. Introduction

Coral reefs occupy a unique niche in marine ecosystems, and national and international efforts are being undertaken to protect and preserve coral reef habitats (Wolanski, 2001). They are one of the most productive ecosystems (Levinton, 2001) and are used as environmental indicators because of their apparent sensitivity to physical and chemical changes in the marine environment (Linton and Warner, 2003), and for evaluation of the impact of various environmental modifications, including sediment supply from terrestrial land (Hodgson, 1989, 1990; Rogers, 1990; Grigg and Dollar, 1991).

Lidz and Hallock (2000) demonstrated that the regional composition of sediment grains around a coral reef

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could indicate changes in the health of the reef tract. Sedimentation of fine particles contributes to a significant disturbance of the marine environment. Striking data from tropical, temperate, and deep-sea communities indicate that sedimentation is a problem that can have ecosystem-level consequences (Rogers, 1990; Burdett, 1992).

The sedimentation process controls the reef environment via its influence on both sediment deposition and suspended sediment, and these, in turn, affect the coral reef community structure differently. Mature coral colonies of some species may survive silt cover for short periods (e.g. hours to days), but coverage for a longer period is lethal to virtually all species (Ruitenbeek *et al*., 1999; Wolanski, 2001; Ismail and Tsuchiya, in preparation). There is also a concern that nutrients contained in the sediment may have a significant effect on coral reef ecosystems. Sedimentation is one of the important factors that govern coral abundance, growth and distribution (Chappell, 1980; Done, 1982; Hubbard, 1986; Hodgson, 1990; Babcock and Davies, 1991; Larcombe and Woolfe, 1999).

The coral reef communities around Ryukyu Islands have been suffering a variety of disturbances since at least 1972 (Nishihira and Yamazato, 1974). Nishihira (1987) reported that the coral reefs and coastal areas of the Ryukyu Islands have been disturbed by various natural and anthropogenic factors such as agricultural and industrial activities. Unfortunately, a number of coral-reef ecosystems are now under serious threat. In common with many other tropical and subtropical waters around the world, the coral reefs of Yaeyama, southern Ryukyus, are experiencing environmental degradation. Red soil sedimentation, caused by land reclamation for agricultural development, has seriously damaged coral habitats; so disastrously that around 70% of Yaeyama coral reefs are reported to be dead, or nearly so (Environment Agency of Japan, 1995).

In the study area, there is a lack of information about the effect and state of sedimentation patterns of fine particles of red soil around the coral reef ecosystem, so our objectives are: 1) to apply the sediment trap method to collect sediment particles depositing in the coral reef ecosystem; 2) to characterize the seasonal and spatial patterns of sedimentation as well as sediment characteristics; 3) to quantify the main nutrients over the corals; and 4) to develop an awareness of how to prevent the damage of coral reef ecosystems and, if it does occur, to allow mitigation measures to be undertaken.

2. Materials and Methods

2.1 Study area

The study was conducted in the coral reefs of the Marine Protected Area around Ishigaki Island and Iriomote Island in the southern part of Ryukyu Islands (Fig. 1), which are known for their extraordinary marine biodiversity and species richness of healthy corals e.g., *Heiopora coerulea*, massive *Porites*, blanching *Porites*, *Montipora*, *Acropora*, large *Galaxea fascicularis*, and *Pavona*, etc. (Masuda *et al*., 1984; Veron, 1988).

Six ordinal sites and one additional site were selected for the monitoring of particle sediment flux according to the level of silt content in the sediment;

1) The south-east side of Ishigaki Island where Shiraho reef flat is located; anthropogenic agricultural development of terrestrial land has occurred in this area. Todoroki River flows through the agriculturally developed area and its flood waters occasionally contain large amounts of reddish soil suspensions. Three sampling stations were constructed on the reef flat: the south side of Todoroki River mouth (Tod-S) and, the north side (Tod-N). The center of Todoroki River mouth (Tod-C) was additionally set when river discharge was extremely high. A pronounced long-shore SW to NE current prevails in the shallow reef flat (2–3 m depth)

2) The west side of Iriomote Island, where the river crosses the anthropogenically undisturbed area and pours river water onto the reef flat: two sampling stations were selected on the reef flat with 2–3 m water depth Sakiyama (Sak-M), and on the reef slope with 4 m water depth, the Sakiyama slope (Sak-Slope) where current and wave energy are relatively high.

3) Kohama (Koh) and Kuroshima (Kuro) Islands, where terrestrial land areas are relatively small and the contribution from inland deposits to the marine ecosystems is relatively low: two sampling stations were selected in the reef flat at 2–3 m water depth.

2.2 Sample collection

2.2.1 Sediment trap moorings

In order to deploy the sediment traps, a transect line was laid out to cross the area ca. 300 m from and perpendicular to the shore line. Sediment traps were placed at either end of the transect lines at 5 ordinal sites (Tod-N, Tod-S, Koh, Kuro, Sak-M) and one additional site (Tod-C) in coral reef flat (2–3 m water depth) and one site (Sak-Slope) on the reef slope (4 m water depth).

One set of sediment traps consisted of three cylindrical PVC tubes, 5.1 cm inner diameter and 12.5 cm length, the top and bottom of which are open and closed, respectively. Each set of sediment traps was attached firmly to a central steel rod stake vertically secured and fixed to the substratum. The base of the trap was placed 30 cm above the substratum. A baffle was placed on the top of each tube. The cell of the baffle required a height-to-width ratio of 2 but less than 6 to prevent settling of the swimmers. The set up resulted in a height to width ratio (2.5), which minimized the capture of sediment

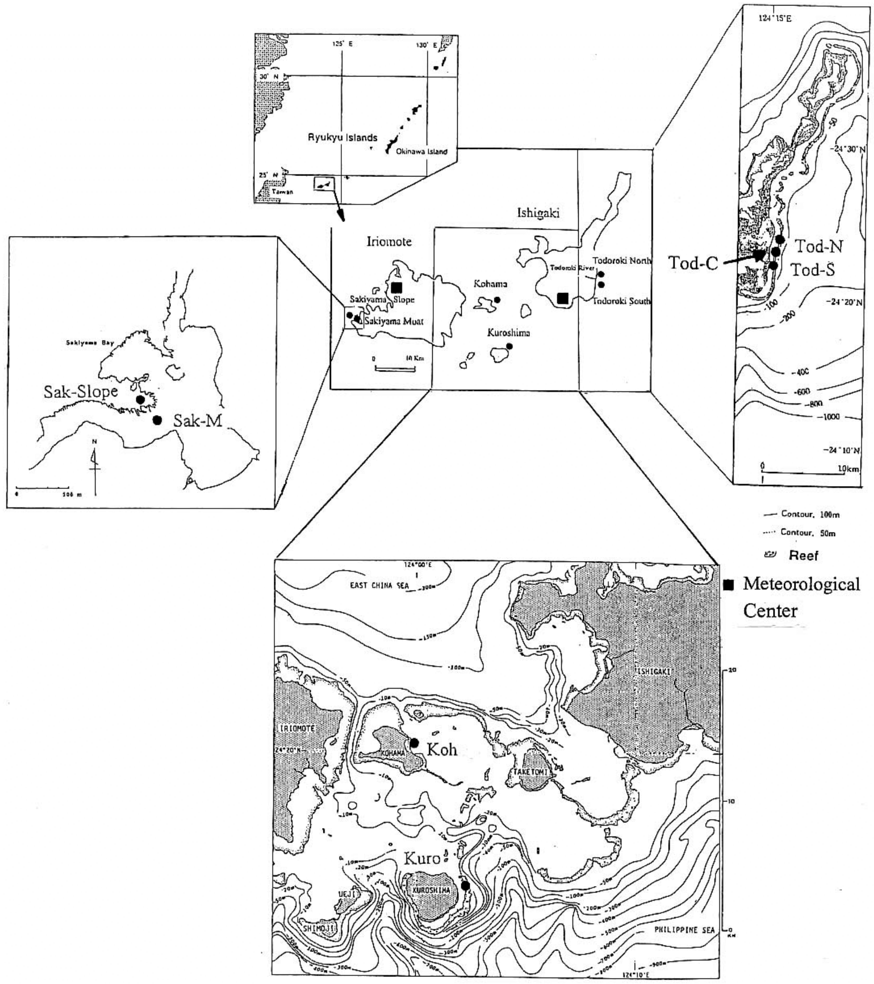

Fig. 1. Location map of the study area and monitoring stations: Sakiyama reef flat (Sak-M), Sakiyama reef slope (Sak-Slope), Iriomote Island; Kohama (Koh); Kuroshima (Kuro); Todoroki North (Tod-N), and Todoroki South (Tod-S) and Todoroki Center (Tod-C), Ishigaki Island, southern Ryukyus, Japan.

resuspension from the bottom, and maximized the particulate collection efficiency (Gardner, 1980). It also reduced the turbulence and retained deposited particles within the traps.

Four sets of sediment traps were placed in each monitoring transect along the coral reef: two sets at a one-meter interval at the beginning of the transect line and the other 2 sets at the end of the transect line. A total of 12 cylinder tube samplers were set at each station. Time-series sediment samples were obtained from September 2000 to September 2001 by recovery of traps at approximately monthly intervals via SCUBA diving. The sediment-trap sampling procedures described above were consistent with the Australian Institute of Marine Science Manual (English *et al.*, 1977) and others (Butman *et al.*, 1986; Ittekkot *et al.*, 1996).

2.2.2 Analytical procedures for trapped particle sediment samples

The collected particles were decanted and stored at 2–4°C in the dark before processing in the laboratory. Samples were then washed with distilled water and dried in an oven at 60°C overnight. Total mass flux was obtained by weighing the dried particle sediments (±0.10 mg). After disaggregating with a rubber pistol, dried samples were separated into seven fractions by sieving through Endicott screens such as 2.00, 1.00, 0.50, 0.25, 0.125 and 0.063 mm, and collecting container, using an electrically driven reciprocating shaker (Model: Retsch, KG-5657, W. Germany).

Total carbon (TC) and total nitrogen (TN) contents of 10 mg ground sub-samples were determined by combustion (830°C) using a Shimazu high sensitivity CN

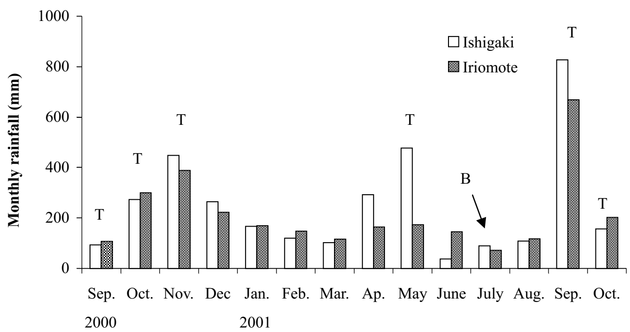

Fig. 2. Monthly rainfall (mm) from September 2000 to October 2001 in the study areas (calculated from the data of Japan Meteorological Center, and Naval Pacific Meteorology and Oceanography Center, 2000 and 2001). T: Typhoon, B: coral bleaching.

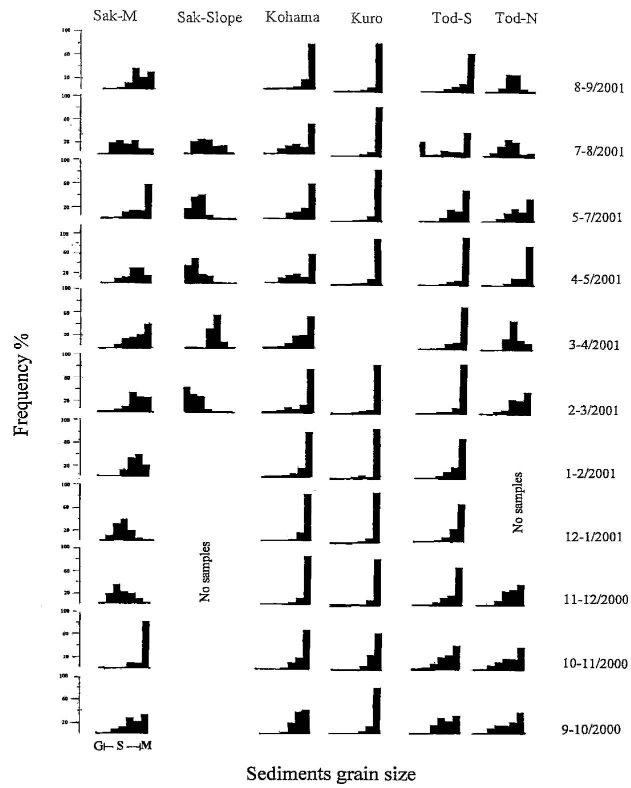

Fig. 3. Grain size distribution patterns shown as histograms of selected trap sediment samples during the monitoring period from September 2000 to September 2001 in the study areas. G: gravel, S: sand, and M: mud.

analyzer (Model: Sumigraph NC-80) as described by Cauwet (1975). Calcium carbonate ($CaCO_3$) content was determined by weight loss before and after leaching the particle sediment samples with 1M HCl for more than overnight.

3. Results

3.1 Rainfall and typhoons

Monthly rainfall data was obtained in the monitoring period between September 2000 and September 2001, calculated from the data of the Meteorological Center, Japan (Fig. 2). The average monthly rainfalls in Ishigaki and Iriomote Islands were 246 and 213 mm respectively, with high average values in October, November and December 2000, and April, May and September 2001. Five typhoons struck the study area during the course of this study in September, October, and November 2000 and May and September 2001 (Japan Meteorological Center; Naval Pacific Meteorology and Oceanography Center, 2000 and 2001). Rainfall is typically heavy during the typhoon seasons

3.2 Particle size distributions

The collected settling particles during the monitoring periods of this study were mostly mud (<0.063 mm) and muddy sand in the reef flat at Tod-N, Tod-S, Tod-C, Koh, Kuro and Sak-M. However, sand and gravel are dominant in the reef slope at Sak-Slope where wave energy is high. Patterns of the particle size distribution of trapped sediments showed a pronounced difference among sites and seasons (Fig. 3). In Koh, Kuro and Tod-S fine particles (mud fraction) generally dominated the whole season, but in the typhoon season rather coarse-grained particles may be present. On the other hand, at Sak-M, Sak-Slope and Td-N, relatively coarse grained sediments dominated.

3.3 Total mass flux

Temporal variations of total mass fluxes at 6 locations are shown in Fig. 4. A pronounced seasonality (high in summer-autumn and low in spring) can clearly be seen at each site except Sak-Slope. Typical seasonal patterns are seen at Sak-M and Koh, where total mass flux was highest during September to November 2000, decreasing to a minimum value between February and April 2001. At Sak-M, the total mass flux increased rapidly from April to September 2001. A similar seasonal pattern was also seen in Kuro and Tod-S, where the total mass flux gradually decreased from September 2000 until April 2001, then increasing until a maximum value was reached during July–August 2001, after which it decreased again during August–September 2001, which is consistent with the seasonal variation of rainfall and frequency of typhoon attack in these regions.

A spatial difference in total mass flux was seen through the year, as follows: Tod-N, Sak-Slope > Koh,

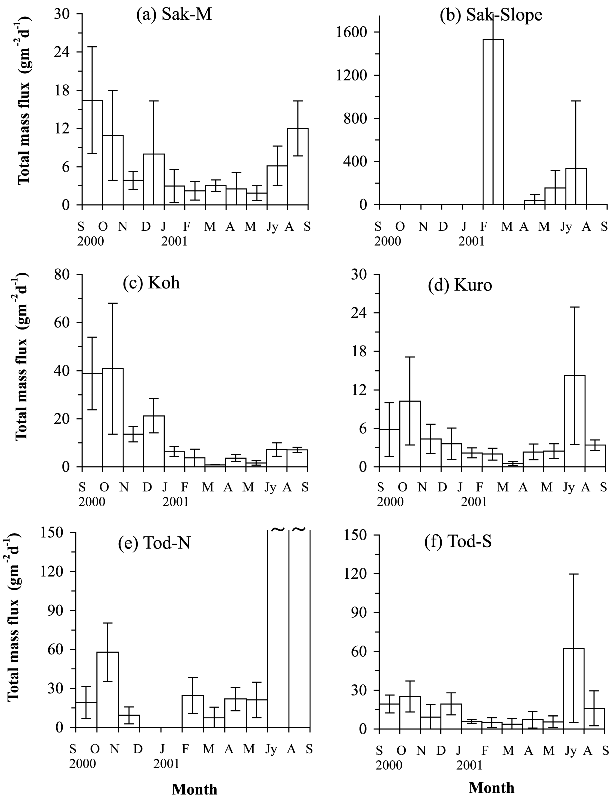

Fig. 4. Total mass flux ($gm^{-2}d^{-1}$) from September 2000 to September 2001 in the study areas, southern Ryukyus, Japan. (a) Sakiyama reef flat (Sak-M), (b) Sak-Slope, reef slope (Iriomote Island), (c) Kohama (Koh), (d) Kuroshima (Kuro), (e) Todoroki North (Tod-N), and (f) Todoroki South (Tod-S) in the reef flat (Ishigaki Island). Data represent mean ± SD.

Tod > Sak-M, Kuro. Exceptionally high values were observed at Sak-Slope during February–March 2001 (1533 $gm^{-2}d^{-1}$), which may be caused by high resuspension of bottom sediments due to the high wave energy at the reef slope, but is not caused by river discharge from land. High flux values at Tod-N during July–August and August–September 2001 (871 and 862 $gm^{-2}d^{-1}$, respectively) is derived from the high river discharge from Todoroki River during the typhoon regime. Relatively high values are also seen at Sak-Slope during May–July 2001 and July–August 2001 (155 and 336 $gm^{-2}d^{-1}$, respectively). Relatively low flux values are seen at Kuro, Sak-M and then Koh, with highest flux values of 14, 16, and 40 $gm^{-2}d^{-1}$, respectively. General total mass flux ranged between 0.54 to 1600 $gm^{-2}d^{-1}$.

It can also be seen that a relatively high total mass flux is related to the size distribution of settled particles collected in the sediment traps. A relatively high flux value and rather coarse grain particles are seen at Sak-Slope (February–March, May–July, July–August 2001), and at Tod-N (July–August, August–September).

3.4 Composition of trapped particle sediment

3.4.1 Total Nitrogen (TN)

Total nitrogen ranged between 0.02 ± 0.01% at Tod-N (August–September 2001) to 0.48 ± 0.04% at Sak-M (March–April 2001), which shows relatively high spatial and seasonal variability. The highest TN % was recorded at Sak-M in March–April 2001: 0.48 ± 0.04%, Tod-S during December to January 2001: 0.44 ± 0.12%, and Kohama in May–July 2001: 0.43 ± 0.17% (Table 1). Generally, there was a notable increase in the nitrogen contents in the studied samples in December 2000–January 2001 and in the period from March to August 2001 at Koh, Kuro, and Sakiyama reef flat compared to other sites, where TN was found to be <0.1%.

3.4.2 Total Carbon (TC)

Total carbon is composed of organic carbon and inorganic carbonate carbon. Values ranged between 4.43 ± 2.08% at Kuro (March–April 2001) to 27.26 ± 1.76% at Tod-S (July–August 2001), with relatively high spatial and seasonal variability. The highest TC % content was recorded at Tod-S and Kuro during July–August 2001 with values of 27.26 ± 1.76 and 26.19 ± 0.73%, respectively (values ± SD). July–August 2001 showed the highest increase of (TC %) at all stations compared to the other months (Table 1).

3.4.3 Carbonate Carbon (CO_3-C)

The carbonate fraction ($CaCO_3$) ranged between 1.92 ± 0.16% at Koh (November–December 2000) to 68.72 ± 2.79% at Tod-C (May–July 2001), also with relatively high spatial and seasonal variability. The highest $CaCO_3$% value was 68.71 ± 2.79 and 32.20 ± 13.03% at Tod-C in May–July, July–August 2001, respectively, and 27.14 ± 3.40% in February–March 2001, 27.12 ± 5.50% in November–December, 2000 and 26.43 ± 4.52% in March–April 2001 at Tod-N. In general, Tod-C and Tod-N stations showed the highest $CaCO_3$% value throughout the monitoring period, higher than other stations. The lowest recorded $CaCO_3$% value was detected at Sak-M, Koh, Kuro and Tod-S (Table 1).

3.4.4 Organic Carbon (OC)

Organic Carbon (OC) was estimated by subtracting Inorganic Carbon (CO_3-C) from TC. {OC = Δ(TC-CO_3-C)}. OC ranged between 3.73 ± 2.63 to 26.42 ± 1.81%. It is typically high (26.43 ± 1.81%), at Tod-S in July–August 2001, and low at Kuro in March–April 2001 (Table 1).

3.4.5 Relationship between OC-NCF and TN-CF at Todoroki stations

The behavior of organic carbon in the non carbonate fraction (OC-NCF) and nitrogen in the carbonate fraction (TN-CF) was studied in detail at Todoroki stations,

Table 1. Monthly variations in the chemical composition of the trapped sediments from September 2000 to September 2001 in the study areas. Todoroki North (Tod-N), Todoroki South (Tod-S), Todoroki Center (Tod-C), Kohama (Koh), Kuroshima (Kuro), Sakiyama reef flat (Sak-M), and Sakiyama Slope (Sak-S). Average values ± SD, calculated *.

Amount of sediment (gm)

	Tod-N	Tod-S	Tod-C	Koh	Kuro	Sak-M	Sak-S
Sep.–Oct.-00	1.20 ± 0.88			3.31 ± 1.80	0.41 ± 0.28	1.18 ± 0.98	
Oct.–Nov.-00	3.82 ± 1.36	1.46 ± 0.73		3.30 ± 2.84	0.83 ± 0.74	0.84 ± 0.63	
Nov.–Dec.-00	0.42 ± 0.28	0.63 ± 0.62		1.02 ± 0.18	0.29 ± 0.16	0.33 ± 0.19	
Dec.–Jan.-01		1.44 ± 0.54		1.55 ± 0.45	0.25 ± 0.16	0.51 ± 0.47	
Jan.–Feb.-01		0.45 ± 0.08		0.43 ± 0.13	0.16 ± 0.07	0.20 ± 0.14	
Feb.–Mar.-01	1.56 ± 0.78	0.34 ± 0.20		0.35 ± 0.41	0.15 ± 0.07	0.18 ± 0.12	90.71 ± 95.89
Mar.–Apr.-01	0.59 ± 0.59	0.28 ± 0.35		0.10 ± 0.00	0.05 ± 0.03	0.26 ± 0.15	1.05
Apr.–May-01	2.17 ± 1.07	0.48 ± 0.40		0.31 ± 0.16	0.18 ± 0.03	0.17 ± 0.15	2.59 ± 2.53
May–Jul.-01	2.97 ± 1.75	0.91 ± 0.79	5.17 ± 3.88	0.27 ± 0.15	0.28 ± 0.10	0.31 ± 0.18	24.02 ± 17.80
Jul.–Aug.-01	60.01 ± 27.78	5.52 ± 3.57	20.76 ± 6.58	0.69 ± 0.24	1.38 ± 1.06	0.61 ± 0.27	20.50 ± 36.63
Aug.–Sep.-01	53.38 ± 23.05	1.30 ± 1.28	61.75 ± 21.40	0.48 ± 0.10	0.26 ± 0.07	0.99 ± 0.30	

Total Nitrogen (TN) (%)

	Tod-N	Tod-S	Tod-C	Koh	Kuro	Sak-M	Sak-S
Sep.–Oct.-00	0.17 ± 0.06			0.08 ± 0.04	0.20 ± 0.10	0.09 ± 0.05	
Oct.–Nov.-00	0.16 ± 0.05	0.12 ± 0.03		0.13 ± 0.04	0.16 ± 0.06	0.09 ± 0.05	
Nov.–Dec.-00	0.19 ± 0.02	0.20 ± 0.03		0.12 ± 0.01	0.17 ± 0.03	0.11 ± 0.07	
Dec.–Jan.-01		0.44 ± 0.13		0.31 ± 0.05	0.38 ± 0.12	0.43 ± 0.04	
Jan.–Feb.-01		0.14 ± 0.03		0.11 ± 0.01	0.11 ± 0.01	0.09 ± 0.05	
Feb.–Mar.-01	0.21 ± 0.02	0.13 ± 0.09		0.11 ± 0.04	0.16 ± 0.04	0.09 ± 0.06	0.06 ± 0.07
Mar.–Apr.-01	0.24 ± 0.03	0.37 ± 0.09		0.37 ± 0.24	0.36 ± 0.16	0.48 ± 0.05	0.03
Apr.–May-01	0.05 ± 0.01	0.18 ± 0.06		0.36 ± 0.12	0.31 ± 0.12	0.23 ± 0.09	0.16 ± 0.23
May–Jul.-01	0.26 ± 0.06	0.24 ± 0.03	0.38 ± 0.04	0.43 ± 0.17	0.36 ± 0.15	0.37 ± 0.21	0.05 ± 0.03
Jul.–Aug.-01	0.03 ± 0.01	0.18 ± 0.13	0.22 ± 0.08	0.38 ± 0.16	0.39 ± 0.13	0.25 ± 0.13	0.04 ± 0.07
Aug.–Sep.-01	0.02 ± 0.01	0.13 ± 0.08	0.03 ± 0.01	0.18 ± 0.05	0.36 ± 0.25	0.04 ± 0.02	

Total Carbon (TC) (%)

	Tod-N	Tod-S	Tod-C	Koh	Kuro	Sak-M	Sak-S
Sep.–Oct.-00	17.53 ± 1.51			18.19 ± 1.74	20.87 ± 0.80	17.60 ± 0.96	
Oct.–Nov.-00	17.47 ± 1.19	18.00 ± 0.14		22.43 ± 0.94	22.30 ± 0.62	18.19 ± 1.75	
Nov.–Dec.-00	13.85 ± 0.74	21.29 ± 0.54		20.57 ± 0.63	13.62 ± 7.34	19.70 ± 2.98	
Dec.–Jan.-01		19.33 ± 0.86		23.58 ± 0.81	19.45 ± 5.52	23.20 ± 0.67	
Jan.–Feb.-01		15.20 ± 0.19		18.63 ± 2.06	12.94 ± 1.34	19.43 ± 2.61	
Feb.–Mar.-01	16.26 ± 1.44	19.94 ± 2.25		21.88 ± 0.60	22.64 ± 1.27	22.23 ± 1.38	22.61 ± 1.40
Mar.–Apr.-01	11.13 ± 4.27	16.66 ± 7.71		19.64 ± 3.19	4.43 ± 2.09	13.42 ± 2.66	15.67
Apr.–May-01	21.17 ± 2.18	22.56 ± 1.28		23.74 ± 7.80	20.27 ± 4.75	20.88 ± 4.59	16.42 ± 0.72
May–Jul.-01	18.41 ± 0.86	19.29 ± 2.16	8.68 ± 0.28	18.43 ± 2.96	21.01 ± 3.28	18.33 ± 6.72	16.12 ± 2.95
Jul.–Aug.-01	24.04 ± 0.82	27.26 ± 1.77	17.36 ± 4.47	24.44 ± 1.36	26.19 ± 0.73	25.66 ± 1.39	25.28 ± 2.73
Aug.–Sep.-01	18.60 ± 1.43	19.43 ± 2.16	19.11 ± 0.69	22.60 ± 1.82	23.42 ± 1.73	20.46 ± 1.13	

Table 1. (continued).

Carbonate Fraction ($CaCO_3$) (%)

	Tod-N	Tod-S	Tod-C	Koh	Kuro	Sak-M	Sak-S
Sep.–Oct.-00	11.56 ± 1.97			2.38 ± 0.55	4.00 ± 1.24	5.54 ± 1.28	
Oct.–Nov.-00	12.71 ± 1.82	3.64 ± 0.94		2.03 ± 1.46	1.28 ± 0.40	3.46 ± 1.27	
Nov.–Dec.-00	27.12 ± 5.51	7.09 ± 4.14		1.92 ± 0.17	2.52 ± 0.78	3.13 ± 2.25	
Dec.–Jan.-01		7.16 ± 0.69		3.33 ± 0.29	3.43 ± 1.33	4.69 ± 1.01	
Jan.–Feb.-01		9.91 ± 4.09		7.48 ± 0.87	5.89 ± 1.40	6.46 ± 2.22	
Feb.–Mar.-01	27.14 ± 3.41	8.79 ± 2.38		6.39 ± 3.34	4.73 ± 0.59	10.86 ± 2.40	8.27 ± 4.33
Mar.–Apr.-01	26.43 ± 4.52	14.27 ± 4.31		8.54 ± 1.72	5.82 ± 2.74	11.13 ± 6.17	2.04
Apr.–May-01	18.09 ± 4.25	9.36 ± 0.48		5.95 ± 0.50	5.85 ± 0.53	9.69 ± 2.42	5.38 ± 6.30
May–Jul.-01	19.83 ± 5.02	14.01 ± 6.69	68.72 ± 2.80	3.44 ± 0.50	4.85 ± 1.13	7.54 ± 2.07	3.41 ± 1.03
Jul.–Aug.-01	10.87 ± 4.65	6.99 ± 2.05	32.20 ± 13.04	5.06 ± 0.37	4.47 ± 0.84	7.58 ± 2.28	3.48 ± 2.55
Aug.–Sep.-01	4.66 ± 0.78	8.83 ± 2.01	9.84 ± 2.13	5.86 ± 0.61	5.11 ± 0.48	5.36 ± 1.24	

Non Carbonate Fraction (%)

	Tod-N	Tod-S	Tod-C	Koh	Kuro	Sak-M	Sak-S
Sep.–Oct.-00	88.44 ± 1.97			97.62 ± 0.55	96.00 ± 1.24	94.46 ± 1.28	
Oct.–Nov.-00	87.29 ± 1.82	96.36 ± 0.94		97.97 ± 1.46	98.72 ± 0.40	96.54 ± 1.27	
Nov.–Dec.-00	72.88 ± 5.51	92.91 ± 4.14		98.08 ± 0.17	97.48 ± 0.78	96.87 ± 2.25	
Dec.–Jan.-01		92.84 ± 0.69		96.67 ± 0.29	96.57 ± 1.33	95.31 ± 1.01	
Jan.–Feb.-01		90.09 ± 4.09		92.52 ± 0.87	94.11 ± 1.40	93.54 ± 2.22	
Feb.–Mar.-01	72.86 ± 3.41	91.21 ± 2.38		93.61 ± 3.34	95.27 ± 0.59	89.14 ± 2.40	91.73 ± 4.33
Mar.–Apr.-01	73.57 ± 4.52	85.73 ± 4.31		91.46 ± 1.72	94.18 ± 2.74	88.87 ± 6.17	97.96
Apr.–May-01	81.91 ± 4.25	90.64 ± 0.48		94.05 ± 0.50	94.15 ± 0.53	90.31 ± 2.42	94.62 ± 6.30
May–Jul.-01	80.17 ± 5.02	85.99 ± 6.69	31.28 ± 2.80	96.56 ± 0.50	95.15 ± 1.13	92.46 ± 2.07	96.59 ± 1.03
Jul.–Aug.-01	89.13 ± 4.65	93.01 ± 2.05	67.80 ± 13.04	94.94 ± 0.37	95.53 ± 0.84	92.42 ± 2.28	96.52 ± 2.55
Aug.–Sep.-01	95.34 ± 0.78	91.17 ± 2.01	90.16 ± 2.13	94.14 ± 0.61	94.89 ± 0.48	94.64 ± 1.24	

Carbonate Carbon (CO_3-C) (%)*

	Tod-N	Tod-S	Tod-C	Koh	Kuro	Sak-M	Sak-S
Sep.–Oct.-00	1.39 ± 0.24			0.29 ± 0.07	0.48 ± 0.15	0.66 ± 0.15	
Oct.–Nov.-00	1.52 ± 0.22	0.44 ± 0.11		0.24 ± 0.18	0.15 ± 0.05	0.42 ± 0.15	
Nov.–Dec.-00	3.25 ± 0.66	0.85 ± 0.50		0.23 ± 0.02	0.30 ± 0.09	0.38 ± 0.27	
Dec.–Jan.-01		0.86 ± 0.08		0.40 ± 0.04	0.41 ± 0.16	0.56 ± 0.12	
Jan.–Feb.-01		1.19 ± 0.49		0.90 ± 0.10	0.71 ± 0.17	0.78 ± 0.27	
Feb.–Mar.-01	3.26 ± 0.41	1.06 ± 0.29		0.77 ± 0.40	0.57 ± 0.07	1.30 ± 0.29	0.99 ± 0.52
Mar.–Apr.-01	3.17 ± 0.54	1.29 ± 0.75		1.02 ± 0.21	0.70 ± 0.33	1.34 ± 0.74	0.24
Apr.–May-01	2.17 ± 0.51	1.12 ± 0.06		0.71 ± 0.06	0.70 ± 0.06	1.16 ± 0.29	0.65 ± 0.76
May–Jul.-01	2.38 ± 0.60	1.68 ± 0.80	8.25 ± 0.34	0.41 ± 0.06	0.58 ± 0.14	0.90 ± 0.25	0.41 ± 0.12
Jul.–Aug.-01	1.30 ± 0.56	0.84 ± 0.25	3.86 ± 1.56	0.61 ± 0.04	0.54 ± 0.10	0.91 ± 0.27	0.42 ± 0.31
Aug.–Sep.-01	0.56 ± 0.09	1.06 ± 0.24	1.18 ± 0.26	0.70 ± 0.07	0.61 ± 0.06	0.64 ± 0.15	

Table 1. (continued).

Organic Carbon {Δ(TC-CO_3-C)} (%)*

	Tod-N	Tod-S	Tod-C	Koh	Kuro	Sak-M	Sak-S
Sep.–Oct.-00	16.14 ± 1.57			17.91 ± 1.67	20.39 ± 0.76	16.93 ± 0.88	
Oct.–Nov.-00	15.95 ± 1.31	17.56 ± 0.08		22.18 ± 0.95	22.15 ± 0.62	17.77 ± 1.62	
Nov.–Dec.-00	10.60 ± 0.99	20.44 ± 0.30		20.34 ± 0.62	13.31 ± 7.29	19.32 ± 2.87	
Dec.–Jan.-01		18.47 ± 0.84		23.18 ± 0.81	19.04 ± 5.65	22.64 ± 0.56	
Jan.–Feb.-01		14.01 ± 0.41		17.73 ± 2.06	12.24 ± 1.20	18.65 ± 2.39	
Feb.–Mar.-01	13.00 ± 1.81	18.89 ± 2.00		21.11 ± 0.71	22.07 ± 1.33	20.93 ± 1.60	21.62 ± 1.83
Mar.–Apr.-01	7.96 ± 3.84	15.36 ± 7.52		18.61 ± 2.98	3.73 ± 2.36	12.09 ± 2.97	15.42
Apr.–May-01	19.00 ± 2.68	21.44 ± 1.23		23.02 ± 7.85	19.57 ± 4.76	19.72 ± 4.53	15.77 ± 1.14
May–Jul.-01	16.03 ± 0.78	17.61 ± 2.10	0.44 ± 0.10	18.02 ± 2.93	20.43 ± 3.42	17.43 ± 6.60	15.71 ± 2.92
Jul.–Aug.-01	22.73 ± 1.23	26.43 ± 1.81	13.50 ± 6.02	23.83 ± 1.32	25.66 ± 0.82	24.75 ± 1.53	24.87 ± 2.66
Aug.–Sep.-01	18.04 ± 1.34	18.37 ± 2.07	17.93 ± 0.75	21.90 ± 1.78	22.81 ± 1.70	19.82 ± 1.22	

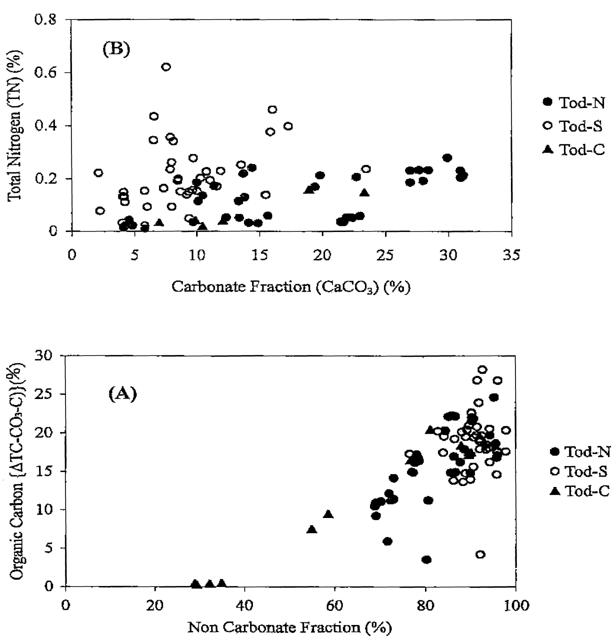

Fig. 5. Binary diagrams showing the behavior of organic carbon in the non carbonate fraction (A), total nitrogen in the carbonate fraction (B) of the analyzed trap sediment samples in the study areas at Todoroki; North (Tod-N), South (Tod-S), and Center (Tod-C), Ishigaki, southern Ryukyus, Japan (from September 2000 to September 2001).

Tod-N, Tod-S, and Tod-C (Figs. 5(A) and (B)). Figure 5(A) shows that OC content of settled sediments is proportional to that of the non carbonate fraction (NCF) because it originated from terrestrial sediments. Organic carbon contained in the non-carbonate fraction shows a notable increase at all stations, especially in August–September 2001. It was relatively higher (15–20%) at Tod-S than Tod-N and Tod-C. Figure 5(B) shows that the carbonate fraction contains relatively higher nitrogen percentages in Tod-S, than Tod-N and Tod-C. It also shows that total nitrogen contents are proportional to that of the carbonate fraction (CF).

3.4.6 $CaCO_3$ and Non-carbonate fraction (NCF)

The carbonate fraction ($CaCO_3$) ranged between 1.92 ± 0.16% at Koh (November–December 2000) to 68.72 ± 2.79% at Tod-C (May–July 2001), which also shows relatively high spatial and seasonal variability. The highest $CaCO_3$% was 68.72 ± 2.80% and 32.20 ± 13.03% at Tod-C in May–July, July–August 2001 respectively, and 27.14 ± 3.40% in February–March 2001, 27.12 ± 5.51% in November–December, 2000 and 26.43 ± 4.52% in March–April 2001 at Tod-N (Table 1). In general, Tod-C and Tod-N stations showed the highest $CaCO_3$% throughout the monitoring period, higher than other stations. The lowest recorded $CaCO_3$% was detected at Sak-M, Koh, Kuro and Tod-S (Table 1). The non-carbonate fraction (NCF) was estimated by subtracting CF from bulk samples. NCF was high at almost all stations, and throughout the sampling period.

4. Discussion

4.1 Seasonal and spatial variation of TN/OC

In order to consider the nutrients derived from suspended particles, the seasonal change in TN/OC ratio of trapped sediments are shown in Fig. 6. It can be seen that the TN/OC ratio is very low compared to the Redfield ratio (C:N ratio of 6:1 or 7:1). The TN/OC ratio is rather small during the typhoon regime, and rather high in samples of December 2000–January, March–April, and May–July 2001 when there is little rainfall. This trend is simi-

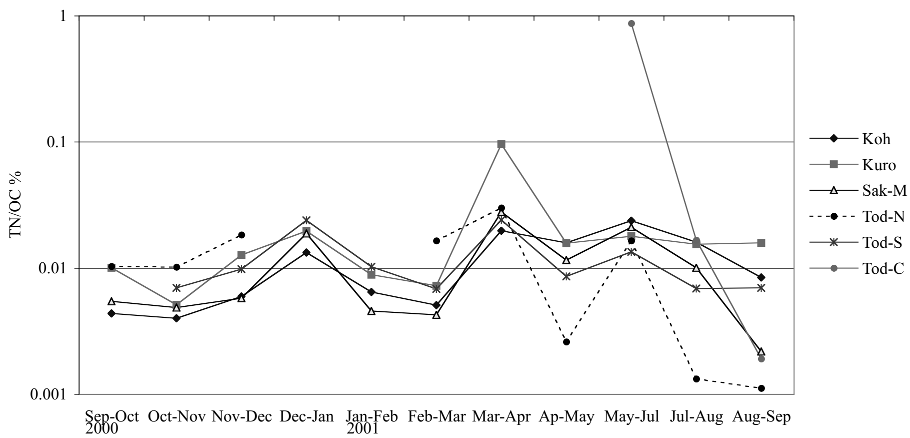

Fig. 6. Monthly variations in the total nitrogen and organic carbon ratio (TN/OC) of the analyzed trap sediment samples in the study areas; Sakiyama reef flat (Sak-M), Kohama (Koh), Kuroshima (Kuro), Todoroki North (Tod-N), and Todoroki South (Tod-S) and Todoroki Center (Tod-C), southern Ryukyus, Japan (from September 2000 to September 2001).

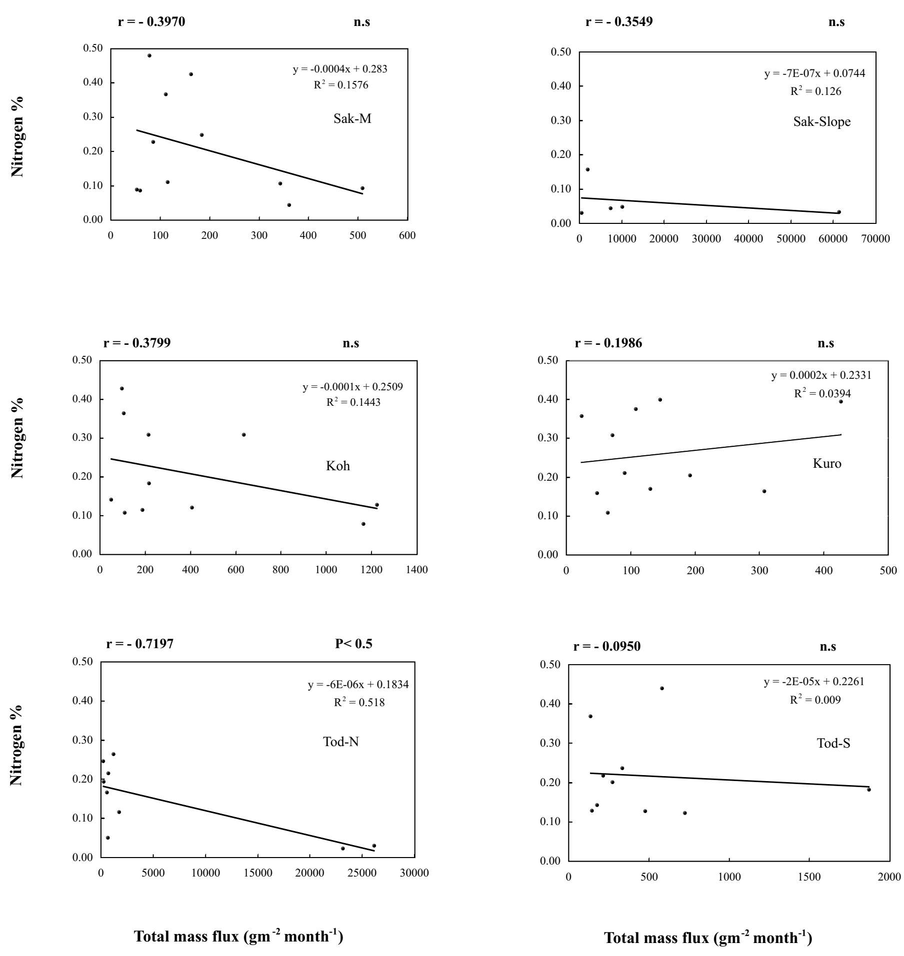

Fig. 7. Correlation between total mass flux ($gm^{-2}Month^{-1}$) and nitrogen % in the study areas from September 2000 to September 2001. r; Pearson's Correlation Coefficient, R^2; Coefficient of determination, P; significance level, n.s.; no significant correlation.

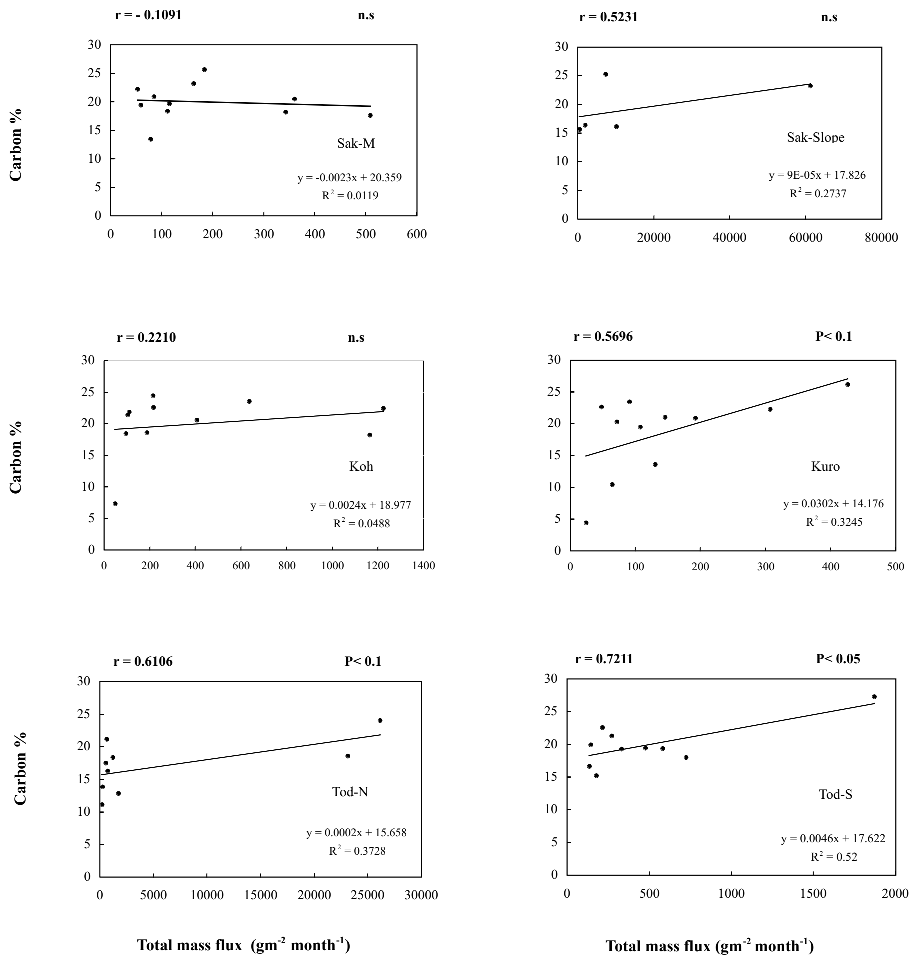

Fig. 8. Correlation between total mass flux (gm^{-2}Month^{-1}) and carbon % in the study areas from September 2000 to September 2001. r; Pearson's Correlation Coefficient, R^2; Coefficient of determination, P; significance level, n.s.; no significant correlation.

lar among all the mooring sites. It is suggested that trapped particle sediments contain N-depleted organic substances, which may be derived from terrestrial land during the typhoon regime, and/or migration of accumulated bottom sediments around the sediment traps, while the contribution of newly formed marine organic substance is rather small.

A rather high TN/OC ratio is seen in May to April in Kuro, which suggests that precipitation is very low, and the contribution from terrestrial land and re-suspension from the bottom sediment are very low, suggesting a mixture of marine origin particles (redfield ratio) and terrestrial sediments.

Tod-C samples show that TN/OC ratio was very high at the beginning of typhoon season, which may be derived from agricultural fields, and may affect coral bleaching. If one compares typhoon and normal seasons, the TN/OC ratio of particle is not very different. According to the TN/OC ratio, river load sediments and re-suspended sediments are similar showing a very low TN/OC ratio. It should be noted that samples with a rather high TN/OC ratio have a high $CaCO_3$ content, with the $CaCO_3$ contained in the rather high particle TN/OC. During the typhoon season values are very low and the particle size distribution shows high proportions of relatively coarse grains.

4.2 *Relationship between total mass flux and TC, TN, and $CaCO_3$*

We compared the results of seasonal and spatial total mass flux and the carbon, nitrogen and carbonate contents using the regression method (Figs. 7–9). Figure 7 shows a proportional relation between the total mass fluxes and the content of carbon, with a positive correlation at all stations. Nitrogen and carbonate contents show an inverse relation with total mass flux, except at Kuro

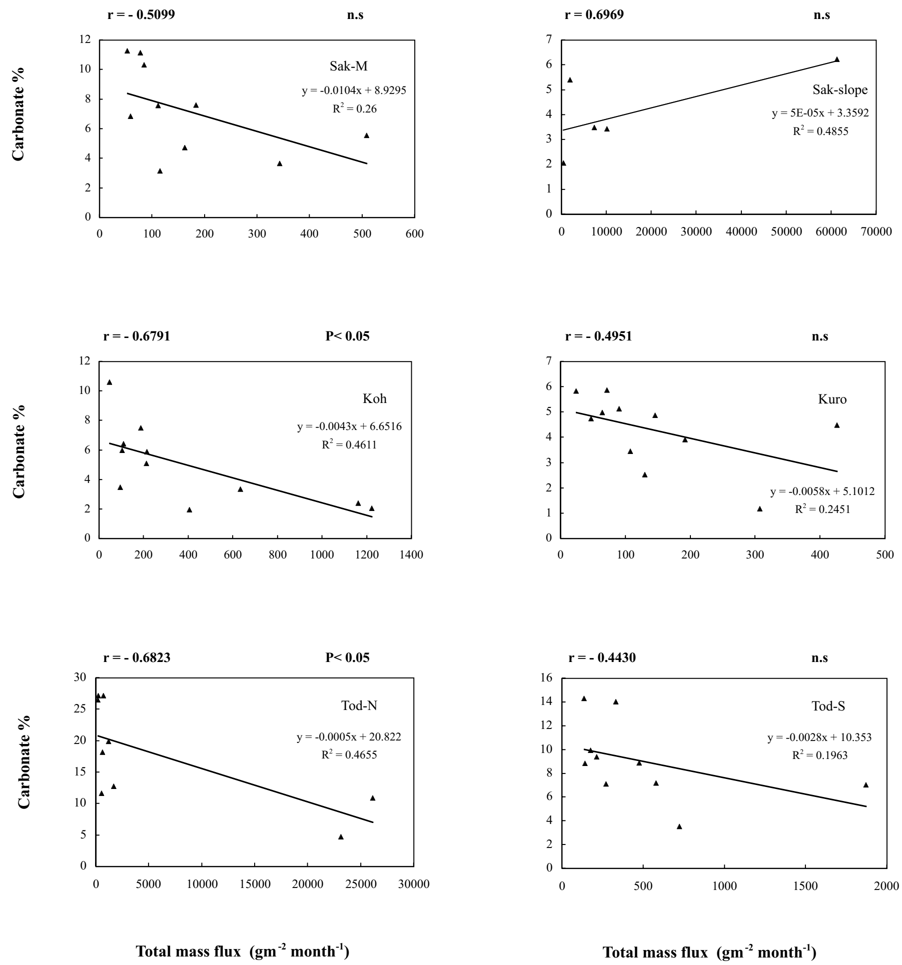

Fig. 9. Correlation between total mass flux ($gm^{-2}Month^{-1}$) and carbonate % in the study areas from September 2000 to September 2001. r; Pearson's Correlation Coefficient, R^2; Coefficient of determination, P; significance level, n.s.; no significant correlation.

and Sak-Slope for nitrogen and carbonate, respectively, which show a positive correlation (Figs. 8 and 9).

The results of total mass fluxes in the study area can be compared with other places: for instance, in this study the observed total mass flux, ranging from 0.54 to 871.9 $gm^{-2}d^{-1}$, is higher than values reported for the Great Barrier Reef, Australia, which ranged from 124 to 616 mg $m^{-2}d^{-1}$ (Kathryn *et al.*, 2001), and in the Venezuelan coral moat: 44 to 281 $gm^{-2}d^{-1}$ (Bastidas *et al.*, 1999).

The total mass fluxes showed a pronounced seasonality, especially in Sak-M, Koh, and Kuro stations where the highest total mass fluxes were reported between July and November compared with the other months at all stations except at Sak-Slope station due to the lack of data from that station (Fig. 4). These values might be related to the seasonal pattern of rainfall and annual typhoon events that struck the study area at that time (Fig. 2).

The mean total mass fluxes were highly variable among stations. The highest total mass fluxes were recorded at Sak-Slope during February to March 2001 (1533.8 $gm^{-2}d^{-1}$) with relatively high values at Tod-N during July to September 2001 (862.6 to 871.9 $gm^{-2}d^{-1}$) compared to the other stations (<70 $gm^{-2}d^{-1}$). The lack of total mass flux data for Sak-Slope (September 2000 to January 2001 and August–September 2001) and Tod-N (September 2000 to January 2001) were due to the accidental loss of sediment traps, which could suggest stronger waves and current actions at Sak-Slope and Tod-N than at other stations during the typhoon regime.

Our results show that the organic carbon contained in the non carbonate fraction increased markedly at all stations, especially in August–September 2001, which may reflect a high river load and rainfall (see also Fig. 2). Organic carbon was relatively higher (15–20%) at Tod-S than Tod-N and Tod-C. Organic carbon was high in a large number of sediments, which means that organic carbon was derived from river load (terrestrial origin).

The carbonate fraction contains relatively higher nitrogen percentages at Tod-S than at Tod-N and Tod-C, especially in May–June 2001, which may also indicate a terrestrial origin. In July–August 2001, the coral bleaching season, higher sedimentation fluxes were recorded at all stations. However, in Tod-C and Tod-S the sediment flux was low, which means that most sediment moved or drifted to the north, and also the south part of Todoroki was not affected by river load like that at Tod-N and Tod-C. Generally, groundwater discharge from adjacent terrestrial areas can be a potentially important nutrient source to coastal coral reefs, contributing significantly to the reef nitrogen budget in the Shiraho area (Umezawa *et al.*, 2002).

Wolanski (1994) and Taylor (1996) also stated that river flood plumes are a relatively local, short-term influence on turbidity on the inner shelf. We noted that the stations close to the river mouths, river plumes on the inner shelf of Ishigaki and Iriomote Islands (Tod-N, Tod-S and Sak-M) have much higher total mass fluxes than those stations located far from river discharge (Koh and Kuro stations). It was also noted that the presence of the coral reefs close to the outlet of the river systems enables the red soil to flow to the corals. We also found an increase of the total mass flux in the Todoroki and Sakiyama reef flat, especially in the rainy and typhoon seasons. Almost similar seasonal patterns of the total mass flux were also recognized, being low from September–July 2000 then increasing dramatically from July to August 2001.

Sedimentation and siltation derived from flushing of rivers and dredging in near-shore areas adversely affect most coastal ecosystems, e.g. coral reefs (Hodgson, 1990). For instance, high turbidity and sedimentation decrease coral abundance, alter coral growth forms to a more branching habitat, and decrease species diversity (Dodge and Vaisnys, 1977; Wesseling *et al.*, 1997). In addition, Marshall and Orr (1931) and Brown and Howard (1985) found that corals are likely to be killed if they are smothered by sediment for more than a few hours. However, larger sediment loads (200 $gm^{-2}d^{-1}$) killed most corals after some continuous exposure (Hodgson, 1997). Therefore, the higher mortality of coral reef species at Tod-N and Tod-S compared to the other stations was expected, due to the high total mass fluxes during July to September 2001 (Minoru *et al.*, in preparation). The long-shore current (SW-NE) at south east Ishigaki Island may affect the sedimentation regime. Therefore, the total mass fluxes were higher at Tod-N than that at Tod-S (Fig. 4).

The total mass flux exerted a different influence on the trends of total nitrogen, carbon and carbonates. Although the correlation coefficients were not high, it is clear that the trends are different between total carbon and nitrogen and carbonates. The increase in carbon percentages with total mass flux may suggest an input of terrestrial supply by rivers because at the same station the amount of carbonates decreased with increasing total mass flux. It may be concluded that the deposited sediments contained organic matter, given their poor nitrogen contents at high total mass fluxes, coinciding with river flash floods that occurred in the rainy season.

The increased particle fluxes in the reef slope, Sakiyama, are consistent with the view of various authors (Monaco *et al.*, 1987, 1990a, 1990b; Walsh *et al.*, 1988) that resuspended particles comprise an increasing proportion of settling material with proximity to the bottom. The hydrodynamic effects involving turbulence and current, the size and composition of settled material, trap design, mooring configuration and movements also influence both rates and types of particles accumulated in traps (Butman *et al.*, 1986; US GOFS, 1989; Gust *et al.*, 1994). Total mass flux results agree with the results that Ohde *et al.* (1982) obtained in Kabira Bay, North West coast of Ishigaki, in terms of their seasonality and the maximum flux in the rainy seasons.

On a long-term basis, the huge amount (872 $gm^{-2}d^{-1}$) of sediment input (red soil and resuspended particles, etc.) as recorded at Todoroki stations may result in lethal effects on coral communities and other benthic organisms. A coral mortality occurred in the area of study, being relatively severe at (Tod-N, Tod-C and Tod-S) from June to September 2001. This was accompanied by high rainfall, excess total mass fluxes, and a rise in the sea water temperature (Minoru *et al.*, in preparation). Based on our results we speculate that the reef environments of south Japan are being affected by long-term continuous loading of sediments, brought about by drainage of the neighboring rivers. The results also stress the importance of conducting seasonal studies of sedimentation over more than one year and at more than one location to gain an understanding of the processes controlling the total mass fluxes in south Japan coral reef ecosystems.

5. Summary

1) For the first time, on the basis of analysis of total mass fluxes and their carbon, nitrogen, carbonate and estimated organic carbon contents of sediments determined monthly from sediment traps along transects in the coral reef ecosystems, in the reef flat as well as reef slope of southern Ryukyus Islands, we discussed and described their seasonal and spatial patterns.

2) We also revealed the seasonal and spatial variability of the quantity of trap sediments, sediment grain size characteristics and fluxes of TC, TN, carbonates and their dependence on the regional changes in the climate and topographic settings.

3) Based on our results we speculate that, over the

long-term, the huge amount of sediment input (red soil and resuspended particles, etc.) may result in lethal effects on coral communities and the benthic organisms.

4) We also speculate that the reef environments of south Japan are being affected by a long-term, continuous loading of sediments, brought about by drainage of the neighboring rivers. The results also stress the importance of conducting seasonal studies of sedimentation over more than one year and at more than one location to gain an understanding of the processes controlling the sedimentation of particulate matter and its formation and export of organic matter in south Japan coral reef ecosystems.

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